DESCRIPTION

HIGH TENSILE COLD-ROLLED STEEL SHEET AND METHOD FOR MANUFACTURING SAME

TECHNICAL FIELD

The present invention relates to a high tensile cold-rolled steel sheet having 590 MPa or higher tensile strength suitable for the reinforcing members of pillar and dashboard of automobile, and the like, specifically to a high tensile cold-rolled steel sheet having a good strength-elongation balance, and showing excellent crashworthiness at about 10 s^{-1} of strain rate, and to a method for manufacturing thereof.

BACKGROUND ART

Conventional high tensile cold-rolled steel sheets having 590 MPa or higher tensile strength (TS) were limited in their use places in the car body because of their poor press-forming property.

For the car body, weight reduction or safety assurance relating to the regulation of gas emissions in view of pollution control has become a recent critical issue. To this point, there has appeared an encouraging movement to adopt the high tensile cold-rolled steel sheets as reinforcing members of pillar and dashboard, and the like. The movement strongly requests to provide the high tensile cold-rolled steel sheets with higher press-forming property and crashworthiness than ever.

In the related art of high tensile cold-rolled steel sheets for automobile, having excellent press-forming property or excellent crashworthiness, JP-A-61-217529, (the term "JP-A" referred to herein signifies the "Japanese Patent Laid-Open Publication"), for example, discloses a high tensile cold-rolled steel sheet having significantly improved elongation by adopting a microstructure containing 10% or more of retained austenite. This high tensile cold-rolled steel sheet, however, is not studied in terms of crashworthiness.

JP-A-11-61327 discloses a high tensile cold-rolled steel sheet having a microstructure which is controlled to have 3 to 30% of area percentage of martensite and 5 μm or smaller average region size of martensite, and having 0.13 or larger work-hardening exponent (n value), 75% or smaller yield ratio, 18000 MPa•% or larger strength-elongation balance, and 1.2 or larger hole-expansion ratio. The crashworthiness of the high tensile cold-rolled steel sheet is evaluated by the n value.

The n value observed in the disclosed patent, however, is determined by a static tensile test (the strain rate per JIS is approximately in a range from 10^{-3} to 10^{-2} s^{-1}). Since a car-crash generates 10 to 10^{3} s^{-1} of strain rate in a reinforcing member, the n value derived from the static tensile test cannot fully evaluate the crashworthiness. To this point, the high tensile cold-rolled steel sheet was re-evaluated taking into account the strain rate on crashing, which is described later, and there was confirmed that satisfactory crashworthiness cannot be attained.

Japanese Patent No. 3253880 discloses a method for

manufacturing high tensile cold-rolled steel sheet having a microstructure structured by ferrite and martensite, and having excellent press-forming property and crashworthiness. The crashworthiness of the high tensile cold-rolled steel sheet is evaluated by the absorbed energy at 2000 s^{-1} of strain rate. The absorbed energy which is determined by that strain rate level is the energy necessary to absorb actually the energy on car-crash by the deformation of the reinforcing member.

JP-A-10-147838 discloses a high tensile cold-rolled steel sheet which improves the crashworthiness by controlling the area percentage of martensite and the ratio of the hardness of martensite to the hardness of ferrite. The hardness of martensite and of ferrite is determined by a Vickers hardness gauge. However, as described in Table 4 on page 189 of "Proceedings of the International Workshop on the Innovative Structural Materials for Infrastructure in 21st Century" [T. Ohmura et al.; "ULTRA-STEEL 2000", National Research Institute for Metals (2000)], the correct hardness of martensite cannot be evaluated by Vickers hardness gauge because the hardness of martensite has a dependency on the size of indentation. According to an investigation given by the inventors of the present invention, no correlation was found between the crashworthiness and the Vickers hardness. The disclosed patent evaluates the crashworthiness by the absorbed energy at 800 s^{-1} of strain rate.

As of the reinforcing members, a member for energy absorption is largely deformed within a very short time on crashing, and the strain rate at that moment reaches to levels from 10^2 to 10^3

s^{-1}. Accordingly, in the related art, the crashworthiness of high tensile cold-rolled steel sheets was evaluated by the absorbed energy and static-dynamic ratio at 10^2 to 10^3 s^{-1} of strain rate, as described in Japanese Patent No. 3253880 and JP-A-10-147838.

The term "static-dynamic ratio" referred to herein is the ratio of the strength determined by a dynamic tensile test at strain rates from 10^2 to 10^3 s^{-1} to the strength determined by a static tensile test at strain rates from 10^{-3} to 10^{-2} s^{-1}. Larger ratio means larger strength and larger absorbed energy on crash.

To improve the crashworthiness of car body, it is also important to protect cabin without deforming the parts to secure life-space of occupants. For the reinforcing members used to those positions, about 10 s^{-1} level of absorbed energy becomes important because the reinforcing members at those positions give smaller deformation than that of the reinforcing members for simply absorbing impact energy, thus giving smaller strain rate even within the same crashing time.

Nevertheless, the related art studied very little the means to improve the absorbed energy at strain rates of about 10 s^{-1}.

DISCLOSURE OF THE INVENTION

An object of the present invention is to provide a high tensile cold-rolled steel sheet having a good strength-elongation balance (TS*EL) and attaining excellent crashworthiness at about 10 s^{-1} of strain rate, and to provide a method for manufacturing thereof.

The characteristics targeted in the present invention are

the following.

(1) Tensile strength: TS ≥ 590 MPa

(2) Strength-elongation balance: TS*El ≥ 16000 MPa•%

(3) Crashworthiness: at 10 s^{-1} of strain rate,

(a) Absorbed energy up to 10% strain: 59 $MJ \cdot m^{-3}$ or larger

(b) Absorbed energy up to 10% strain per 1 MPa of tensile strength: 0.100 $MJ \cdot m^{-3}$/MPa or larger

The above object is attained by a high tensile cold-rolled steel sheet: consisting essentially of 0.04 to 0.13% C, 0.3 to 1.2% Si, 1.0 to 3.5% Mn, 0.04% or less P, 0.01% or less S, 0.07% or less Al, by mass, and balance of Fe and inevitable impurities; having a microstructure containing 50% or larger area percentage of ferrite and 10% or larger area percentage of martensite, and having 0.85 to 1.5 of ratio of intervals of the martensite in the rolling direction to those in the sheet thickness direction; and having 8 GPa or larger nano strength of the martensite.

The high tensile cold-rolled steel sheet can be manufactured by a method having the steps of: hot-rolling a steel slab having the above composition, into a steel sheet, followed by coiling the steel sheet at coiling temperatures ranging from 450°C to 650°C; cold-rolling the coiled steel sheet at cold-rolling reductions ranging from 30 to 70%; annealing the cold-rolled steel sheet by heating to a temperature region of [the coiling temperature + the cold-rolling reduction percentage x 4.5] - [the coiling temperature + the cold-rolling reduction percentage x 5.5] (°C);

and cooling the annealed steel sheet to temperatures of 340°C or below at average cooling rates of 10°C/s or more.

BRIEF DESCRIPTION OF THE DRAWING

Figure 1 is a sketch illustrating the method for determining the ratio of intervals of the martensite in the rolling direction to that in the sheet thickness direction.

EMBODIMENTS FOR CARRYING OUT THE INVENTION

Although precise measurement of stress-strain relation at strain rates around 10 s^{-1} was very difficult, a recently developed sensing block type impact tensile tester has allowed the precise measurement thereof.

The inventors of the present invention applied the sensing block type impact tensile tester to investigate the absorbed energy of high tensile cold-rolled steel sheet at strain rates around 10 s^{-1}, and derived the following findings.

1) To increase the absorbed energy, it is important to control the microstructure so as the area percentage of ferrite to become 50% or larger, the area percentage of martensite to become 10% or larger, and the ratio of intervals of the martensite in the rolling direction to that in the sheet thickness direction to become a range from 0.85 to 1.5, and to bring the nano hardness of the martensite to 8 GPa or larger.

2) To attain that microstructure, it is important to adjust the balance of ingredients mainly of C, Mn, and Si, and to control appropriately the coiling temperature, the cold-rolling reduction,

the annealing temperature, and the cooling rate after annealing. In particular, the strength-elongation balance and the crashworthiness are improved by setting higher annealing temperature when the coiling temperature and the cold-rolling reduction are at high level, thereby forming the martensite while minimizing the formation of a banded structure.

3) With the actions of 1) and 2), the high tensile cold-rolled steel sheet attains higher absorbed energy than that of conventional high tensile cold-rolled steel sheet having the same tensile strength therewith.

The present invention has been perfected based on these findings. The detail of the present invention is described in the following.

1. Ingredients

C:

The C content is required to be 0.04% by mass or more to control the tensile strength appropriately and to assure the area percentage of martensite to 10% or larger. If, however, the C content exceeds 0.13% by mass, the weldability significantly deteriorates. Accordingly, the C content is specified to a range from 0.04 to 0.13% by mass, and preferably from 0.07 to 0.12% by mass.

Si:

Silicon is an important element to control the dispersed state of martensite and to control the nano hardness of the martensite. To prevent the softening of the martensite during

cooling after annealing, the Si content is required to be 0.3% by mass or more. If, however, the Si content exceeds 1.2% by mass, the effect saturates, and the chemical conversion treatment performance significantly deteriorates. Consequently, the Si content is specified to a range from 0.3 to 1.2% by mass, and preferably from 0.4 to 0.7% by mass.

Mn:

The Mn content is required to be 1.0% by mass or more to assure 590 MPa or higher tensile strength. Manganese is extremely effective to increase the nano hardness of martensite. If, however, the Mn content exceeds 3.5% by mass, the strength significantly increases, and the elongation largely decreases. Therefore, the Mn content is specified to a range from 1.0 to 3.5% by mass, and preferably from 2.3 to 2.8% by mass.

P:

Phosphorus segregates in prior-austenite grain boundary to deteriorate the low temperature toughness, and also segregates in steel to increase the anisotropy of steel sheet, thus deteriorating the workability. Accordingly, the P content is specified to 0.04% by mass or less, and preferably 0.02% by mass or less. Smaller P content is more preferable.

S:

When S segregates in prior-austenite grain boundary or when large amount of S precipitates as MnS, the low temperature toughness decreases, and hydrogen crack tends to occur. Consequently, the S content is specified to 0.01% by mass or less, and preferably 0.006% by mass or less. Smaller S content is more preferable.

Al:

Aluminum is added as an effective element to deoxidizing steel to improve the cleanliness thereof. To attain the effect, the Al content is preferably adjusted to 0.001% by mass or more. If, however, the Al content exceeds 0.07% by mass, a large amount of inclusions appears to cause flaws on the cold-rolled steel sheet. Therefore, the Al content is specified to 0.07% by mass or less, and preferably 0.05% by mass or less.

Balance includes Fe and inevitable impurities. The inevitable impurities are N, O, Cu, and the like. Since N enhances aging and deteriorates elongation properties, the N content is preferably limited to 0.005% by mass or less.

Other than the above basic elements, addition of at least one element selected from the group consisting of 0.5% or less Cr, 0.3% or less Mo, 0.5% or less Ni, and 0.002% or less B, by mass is effective to improve the quenchability and to control the amount of martensite.

Cr:

Chromium is preferably added by an amount of 0.02% by mass or more to improve the quenchability and to control the amount of martensite. However, the Cr content exceeding 0.5% by mass deteriorates the performance of electrodeposition coating which is given to the press-formed parts. Accordingly, the Cr content is specified to 0.5% by mass or less, and preferably 0.2% by mass or less.

Mo:

Molybdenum is preferably added by an amount of 0.05% by

mass or more to improve the quenchability and to control the amount of martensite. If, however, the Mo content exceeds 0.3% by mass, the cold-rolling performance deteriorates. Consequently, the Mo content is specified to 0.3% by mass or less, and preferably 0.2% by mass or less.

Ni:

Nickel is preferably added by an amount of 0.05% by mass or more to improve the quenchability and to control the amount of martensite. If, however, the Ni content exceeds 0.5% by mass, the cold-rolling performance deteriorates. Consequently, the Ni content is specified to 0.5% by mass or less, and preferably 0.3% by mass or less.

B:

Boron is preferably added by the amount of 0.0005% by mass or more to improve the quenchability and to control the amount of martensite. If, however, the B content exceeds 0.002% by mass, the cold-rolling performance deteriorates. Consequently, the B content is specified to 0.002% by mass or less, and preferably 0.001% by mass or less.

Other than the previously described basic ingredients, or other than the basic ingredients with the addition of above elements, the addition of at least one element selected from the group consisting of 0.05% or less Ti and 0.05% or less Nb, by mass, is more effective in improving the quenchability, refining the ferrite, and controlling the dispersion of martensite.

Ti:

Titanium is preferably added by an amount of 0.005% by mass

or more to refine the ferrite grains and thus to control the dispersion of martensite. If, however, the Ti content exceeds 0.05% by mass, the effect saturates. Therefore, the Ti content is specified to 0.05% by mass or less, and preferably from 0.005 to 0.02% by mass or less.

Nb:

With the similar reason to that of Ti, the Nb content is specified to 0.05% by mass or less, and preferably from 0.005 to 0.02% by mass.

2. Structure

2-1. Area percentage of ferrite

To attain 16000 MPa•% or larger strength-elongation balance (TS*El), the area percentage of ferrite is required to be adjusted to 50% or larger. If the area percentage of the ferrite is smaller than 50%, the amount of hard phase other than the ferrite becomes large, which results in excess strength to deteriorate the strength-elongation balance. At strain rates around 10 s^{-1}, since the increase in the stress during deformation of ferrite is large, if the area percentage of ferrite is small, the absorbed energy cannot be increased. Accordingly, the area percentage of ferrite is preferably in a range from 60 to 80%.

2-2. Area percentage of martensite

To attain 16000 MPa•% or larger strength-elongation balance (TS*El) and to improve the crashworthiness, the area percentage of martensite is required to be adjusted to 10% or more. If the

area percentage of martensite is smaller than 10%, satisfactory crashworthiness cannot be attained. The area percentage of martensite is preferably in a range from 20 to 40%.

Other than the ferrite and the martensite, the presence of austenite, bainite, cementite, pearlite, and the like is acceptable. These additional phases, however, are preferably less as far as possible, and 10% or smaller area percentage thereof is preferred. In particular, since the austenite deteriorates the crashworthiness, the area percentage of austenite is preferably adjusted to smaller than 3%.

The determination of area percentage of ferrite, martensite, and other phases was conducted by: mirror-polishing the sheet-thickness cross section in the rolling direction of the steel sheet; etching the polished surface using a 1.5% nital; observing the etched surface using a scanning electron microscope (SEM) at a position of 1/4 sheet thickness to prepare photographs (at x1000 magnification); and then processing the photographs by an image-analyzer.

2-3. Ratio of intervals of martensite

To attain 16000 MPa•% or larger strength-elongation balance (TS*El), and to attain 59 $MJ \cdot m^{-3}$ or higher absorbed energy up to 10% strain at 10 s^{-1} or larger strain rate, and 0.100 $MJ \cdot m^{-3}/MPa$ or higher absorbed energy up to 10% strain per 1 MPa of tensile strength, the ratio of intervals of the martensite in the rolling direction to that in the sheet thickness direction, (the ratio of intervals of martensite), is required to be adjusted to a range

from 0.85 to 1.5. If the ratio becomes smaller than 0.85 or larger than 1.5, sufficient elongation and crashworthiness cannot be attained.

Since martensite is harder than ferrite, and thus becomes a hindrance to the migration of dislocation (strain), the dislocation preferentially moves through a region free from martensite. As a result, when the ratio of intervals of martensite exceeds 1.5, that is, when the intervals of phases in the rolling direction widens larger than the intervals of phases in the sheet thickness direction, or when the ratio of intervals of martensite becomes smaller than 0.85, that is, when the intervals of phases in the sheet thickness direction becomes wider than those in the rolling direction, the dislocation moves through a region of wide intervals of phases, or through a region without the martensite. As a result, sufficient elongation and crashworthiness cannot be attained.

To the contrary, when the ratio of intervals of martensite is between 0.85 and 1.5, and is close to 1, that is, when there is not much difference between the intervals of phases in the sheet thickness direction and those in the rolling direction, the migration of dislocation is suppressed by the martensite, which increases the amount of accumulated dislocation to increase the deformation stress, thereby improving the crashworthiness. In addition, the elongation also increases because the distribution of martensite becomes relatively uniform.

The ratio of intervals of martensite is preferably in a range from 1.0 to 1.3.

According to the cold-rolled steel sheet of the present invention, the ratio of intervals of martensite in the sheet width direction to those in the sheet thickness direction tends to become close to 1 compared with the ratio of intervals of the phases in the rolling direction to those in the sheet thickness direction. According to the present invention, therefore, the direction which maximizes the intervals of martensite is represented by the rolling direction, and the degree of dispersion of martensite is evaluated by the ratio of intervals of phases in the rolling direction to those in the sheet thickness direction.

The ratio of intervals of martensite was determined as follows.

Steel sheet cross section in the rolling direction was observed by SEM. On thus prepared photograph of the section, taken at x1000 magnification, five lines having 50 μm in width were drawn at spacing of 20 μm or more each in the rolling direction and in the sheet thickness direction. The intervals of martensite existing on each of the lines were measured, and the average intervals thereof in each of the rolling direction and the sheet thickness direction were derived, and then the ratio of the respective average intervals was adopted as the ratio of intervals of phases.

The procedure to determine the ratio of intervals of martensite is described below referring to Fig. 1, where a single line is drawn in each of the rolling direction and the sheet thickness direction.

The average intervals of martensite in the rolling direction

are $(a_1 + a_2 + a_3 + a_4 + a_5)/5$, while those in the sheet thickness direction are $(b_1 + b_2 + b_3)/3$.

Therefore, the ratio of intervals of martensite is expressed by

$\{(a_1 + a_2 + a_3 + a_4 + a_5)/5\}/\{(b_1 + b_2 + b_3)/3\}$.

3. Nano hardness of martensite

To attain 59 $MJ \cdot m^{-3}/MPa$ or higher absorbed energy up to 10% strain, and to attain 0.100 $MJ \cdot m^{-3}/MPa$ or higher absorbed energy up to 10% strain per 1 MPa of tensile strength, at 10 s^{-1} of strain rate, the nano hardness of martensite is further requested to be adjusted to 8 GPa or more.

If the nano hardness is smaller than 8 GPa, the strength-elongation balance and the crashworthiness deteriorate. A presumable reason of the deterioration is that, when the nano hardness of martensite is small and when the deformation stress of martensite is small, the effect of the martensite to suppress the migration of dislocation becomes weak. Larger nano hardness of martensite is more preferable, and 10 GPa or larger nano hardness thereof is preferable.

The nano hardness of martensite is the hardness determined by the following procedure.

Surface of a steel sheet is ground to a position of 1/4 sheet thickness, and the surface is treated by electropolishing to remove the grinding strain. The hardness of martensite on the polished surface is determined at 15 points using TRIBOSCOPE (Hysitron, Inc.), and the average value of the 15 point values

is adopted as the nano hardness. The measurement was given on almost equal indentation sizes. That is, the determination of hardness was given by adjusting the load so as the contact depth which is proportional to the size of indentation to become 50±20 nm. One side of the indentation was about 350±100 nm.

4. Manufacturing method

After preparing a molten steel adjusted to above composition by a known method such as the one applying converter, a steel slab was prepared by casting the molten steel by a known method such as continuous casting process. Then, the steel slab was heated, followed by hot-rolling by a known method to obtain a steel sheet.

4-1. Coiling temperature

The hot-rolled steel sheet is required to be coiled at coiling temperatures ranging from 450°C to 650°C. If the coiling temperature is below 450°C, the strength of steel sheet increases to increase the possibility of fracture thereof during cold-rolling. If the coiling temperature exceeds 650°C, the banded structure significantly develops and remains even after cold-rolling and annealing, which fails to control the ratio of intervals of martensite within a desired range. The coiling temperature is preferably in a range from 500°C to 650°C.

4-2. Cold-rolling reduction

The coiled steel sheet is required to be cold-rolled at

cold-rolling reductions ranging from 30 to 70%. If the cold-rolling reduction is smaller than 30%, the structure becomes coarse, and the target ratio of intervals of martensite becomes smaller than 0.85, thereby deteriorating both the elongation and the crashworthiness. If the cold-rolling reduction exceeds 70%, banded structure is formed after annealing, and the ratio of intervals of martensite exceeds 1.5.

4-3. Heating temperature during annealing

Since, even within the range of the present invention, high coiling temperature and high cold-rolling reduction likely generate the banded structure, the annealing needs to be given at elevated temperatures to avoid the formation of band structure. To do this, the heating temperature during annealing is required to be varied depending on the coiling temperature and the cold-rolling reduction, or to be required to enter a temperature region of [the coiling temperature + the cold-rolling reduction percentage x 4.5] - [the coiling temperature + the cold-rolling reduction percentage x 5.5] (°C). If the heating temperature is below [the coiling temperature + the cold-rolling reduction percentage x 4.5], the banded structure cannot be diminished, the desired ratio of intervals of martensite cannot be attained, and further the diffusion of substitution elements such as Si and Mn becomes insufficient, thereby failing in attaining 8 GPa or larger nano hardness of martensite. If the heating temperature exceeds [the coiling temperature + the cold-rolling reduction percentage x 5.5] (°C), the austenite diffuses nonuniformly during

heating, which fails to attain the desired ratio of intervals of martensite. Furthermore, the nano hardness of martensite cannot be increased to 8 GPa or larger, thus deteriorating the elongation and the crashworthiness presumably because the austenite become coarse and the martensitic block size after annealing becomes coarse.

To bring the ratio of intervals of martensite to further preferable range from 1.0 to 1.3, it is preferred to conduct heating within an austenite single phase region above the Ac3 transformation point, while not exceeding the above upper limit temperature. Particularly when the cold-rolling reduction is 60% or larger, heating is preferably done in the austenite single phase region.

The holding time during heating is preferably 30 seconds or more because less than 30 seconds of heating may form martensite at 10% or larger area percentages after annealing and may raise difficulty in attaining stable characteristics over the whole length of the coil. If, however, the holding time exceeds 60 seconds, the effect saturates, and the manufacturing cost increases. Therefore, the holding time is preferably not more than 60 seconds.

4-4. Cooling condition after annealing

The annealed steel sheet is required to be cooled to 340°C or below at cooling rates of 10°C/sec or higher. If the cooling rate is lower than 10°C/sec, or if the cooling-stop temperature exceeds 340°C, the desired nano hardness of martensite cannot

be attained. The cooling rate referred to herein is the average cooling rate between the lower limit temperature of the above heating temperatures, or [the coiling temperature + the cold-rolling reduction percentage x 4.5] (°C), and the temperature to cool at cooling rates of 10°C/sec or higher.

If the cooling rate exceeds 50°C/sec, the cooling likely becomes nonuniform, and the desired characteristics in the width direction of the steel sheet may not be attained. Accordingly, the cooling rate is preferably adjusted to 50°C/sec or smaller.

The temperature for cooling at that cooling rate is preferably adjusted to 300°C or below, and 270°C or below is more preferable.

The treatment after the cooling at that cooling rate is not specifically limited. For example, cooling to room temperature may be given by a known method such as air-cooling (allowing standing) and slow-cooling. The reheating after the cooling, however, should be avoided because the reheating tempers to soften the martensite.

As described above, since the annealed steel sheet is required to be rapidly cooled at cooling rates of 10°C/sec or higher, the annealing is advantageously conducted in a continuous annealing furnace. The 30 seconds or longer holding time in the continuous annealing process can be attained by selecting the annealing temperature (ultimate highest temperature in the continuous annealing) to a temperature in the above heating temperature region, and by holding the steel within the temperature region for 30 seconds or more. For example, the soaking time

(or called the "annealing time") at the annealing temperature may be selected to 30 seconds or more, or, after reaching the annealing temperature, the steel may be slowly cooled to the lower limit of the above heating temperature region, while adjusting the retention time in the heating temperature region to 30 seconds or more.

Example 1

Steel Nos. A to ZZ having the respective compositions given in Table 1-1 and Table 1-2 were ingoted by a converter, and then they were treated by continuous casting to prepare the respective slabs. These slabs were heated to temperatures ranging from 1100°C to 1250°C, followed by hot-rolling, thus prepared the respective steel sheets having thicknesses given in Table 2-1 and Table 2-2. These steel sheets were coiled at the respective coiling temperatures given in Table 2-1 and Table 2-2. Then, cold-rolling, continuous annealing, and controlled cooling were given to these steel sheets under the conditions given in Table 2-1 and Table 2-2, thus obtained the respective high tensile cold-rolled steel sheet Nos. 1 to 39.

The Ac3 transformation point given in Table 1-1 and Table 1-2 was determined by preparing samples from the respective sheet bars after hot-rough-rolling, using Thermec Master Z of Fuji Electronics Industrial Co., Ltd.

Thus prepared respective high tensile cold-rolled steel sheets were subjected to structural observation, ordinary static tensile test, sensing block type high speed tensile test at 10

s^{-1} of strain rate, and nano hardness test.

The structural observation and the nano hardness test were given by the above-described methods, thereby determining the area percentage of ferrite and martensite, the ratio of intervals of martensite, and the nano hardness of martensite.

The ordinary static tensile test and the sensing block type high speed tensile test at 10 s^{-1} of strain rate were given by the following methods.

i) Static tensile test: With a JIS No.5 specimen defining the direction lateral to the rolling direction as the longitudinal direction, the tensile strength TS and the elongation El were determined in accordance with JIS Z2241.

ii) Sensing block type high speed tensile test: The tensile test was given in the lateral direction to the rolling direction at 10 s^{-1} of strain rate, using a Sensing block type impact tensile tester (TS-2000, Saginomiya Seisakusho, Inc.) The absorbed energy up to 10% strain and the absorbed energy up to 10% strain per 1 MPa of tensile strength were determined.

The results are given in Table 3-1 and Table 3-2.

The high tensile cold-rolled steel sheet Nos. 1, 3, 5, 7, 8, 10, 12, 14 to 19, 21 to 23, 29 to 34, and 37 to 39, which were the Examples of the present invention, showed 590 MPa or higher tensile strength and 16000 MPa•% or higher excellent strength-elongation balance, further gave 59 $MJ \cdot m^{-3}$ or higher absorbed energy up to 10% strain at 10 s^{-1} of strain rate, and 0.100 $MJ \cdot m^{-3}/MPa$ or higher absorbed energy up to 10% strain per 1 MPa of tensile strength, which proves their excellent

crashworthiness.

Table 1-1

Steel No.	Chemical composition (mass%)													Ac_3 (℃)
	C	Si	Mn	P	S	Al	N	Cr	Mo	Ni	B	Ti	Nb	
A	0.061	0.41	2.78	0.013	0.005	0.035	0.004	-	-	-	-	-	-	878
B	0.122	0.32	2.64	0.015	0.004	0.032	0.003	-	-	-	-	-	-	853
C	0.090	0.57	2.58	0.012	0.005	0.037	0.004	-	-	-	-	-	-	875
D	0.082	0.68	2.01	0.010	0.003	0.024	0.004	-	-	-	-	-	-	882
E	0.055	0.46	1.54	0.012	0.005	0.034	0.003	-	-	-	-	-	-	883
F	0.100	0.49	2.46	0.014	0.004	0.036	0.004	-	-	-	-	-	-	868
G	0.085	0.69	2.72	0.013	0.003	0.021	0.005	-	-	-	-	-	-	882
H	0.115	0.42	2.35	0.009	0.002	0.027	0.004	-	-	-	-	-	-	860
I	0.095	0.92	2.50	0.015	0.004	0.034	0.003	-	-	-	-	-	-	889
J	0.075	0.53	2.41	0.013	0.001	0.036	0.003	0.03	-	-	-	-	-	878
K	0.079	0.51	2.37	0.014	0.003	0.029	0.004	-	0.1	-	-	-	-	879
L	0.092	0.35	2.13	0.012	0.002	0.040	0.002	-	-	0.08	-	-	-	864
M	0.086	0.55	2.31	0.010	0.004	0.033	0.003	-	-	-	0.0005	-	-	875
N	0.071	0.42	2.36	0.008	0.003	0.035	0.004	-	0.06	-	0.0008	-	-	877

Table 1-2

Steel No.	Chemical composition (mass%)													Ac_3 (℃)
	C	Si	Mn	P	S	Al	N	Cr	Mo	Ni	B	Ti	Nb	
O	0.087	0.64	2.69	0.014	0.005	0.026	0.003	-	-	-	-	0.009	-	879
P	0.092	0.59	2.53	0.011	0.004	0.032	0.004	-	0.05	-	-	0.006	-	876
Q	0.033	0.68	2.53	0.012	0.003	0.025	0.004	-	-	-	-	-	-	902
R	0.105	0.21	2.38	0.010	0.005	0.038	0.004	-	-	-	-	-	-	854
S	0.098	0.43	0.82	0.013	0.002	0.033	0.003	-	-	-	-	-	-	866
T	0.075	0.54	3.8	0.013	0.002	0.033	0.004	-	-	-	-	-	-	879
U	0.152	0.72	2.69	0.013	0.002	0.033	0.003	-	-	-	-	-	-	863
V	0.052	0.47	1.42	0.033	0.003	0.032	0.005	-	-	-	-	-	-	885
W	0.125	0.39	1.58	0.025	0.003	0.037	0.004	-	-	-	-	-	-	856
X	0.075	0.51	2.39	0.029	0.005	0.025	0.005	-	-	-	-	-	-	877
Y	0.077	0.99	1.27	0.010	0.003	0.020	0.004	-	-	-	-	-	-	898
Z	0.072	0.55	2.56	0.018	0.003	0.036	0.003	-	-	-	-	-	0.012	880
ZZ	0.108	0.63	2.61	0.013	0.004	0.035	0.003	-	-	-	-	0.018	0.014	871

* Underline designates outside the range of the invention.

Table 2-1

Steel sheet No.	Steel No.	Coiling temperature (°C)	Hot-rolled sheet thickness (mm)	Cold-rolling reduction (%)	Cold-rolled sheet thickness (mm)	[Coiling temperature + cold-rolling reduction percentage x 4.5] (°C)	[Coiling temperature + cold-rolling reduction percentage x 5.5] (°C)	Maximum heating temp. (°C)	Holding time in heating temp. region (s)	Average cooling rate (°C/s)	Temp. of forcefully stop cooling (°C)	Remark
1	A	600	3.2	50	1.6	825	875	830	30	20	250	Example
2	A	600	2.2	27	1.6	722	749	730	60	20	250	Comparative example
3	B	600	3.2	44	1.8	798	842	810	90	25	275	Example
4	B	600	3.2	44	1.8	798	842	760	90	25	275	Comparative example
5	C	550	3.0	53	1.4	789	842	820	80	20	250	Example
6	C	550	4.8	71	1.4	870	941	880	80	20	250	Comparative example
7	D	600	2.4	50	1.2	825	875	860	60	30	220	Example
8	E	450	2.4	58	1.0	711	769	850	110	40	200	Example
9	E	450	2.4	58	1.0	711	769	800	110	40	200	Comparative example
10	F	650	3.0	40	1.8	830	870	840	60	15	240	Example
11	F	650	3.0	40	1.8	830	870	840	60	5	240	Comparative example
12	G	600	2.0	50	1.0	825	875	840	90	40	250	Example
13	G	600	2.0	50	1.0	825	875	840	90	40	350	Comparative example
14	H	500	3.2	50	1.6	725	775	770	90	20	230	Example
15	I	550	3.2	44	1.8	748	792	780	80	20	260	Example
16	J	600	2.6	46	1.4	807	853	820	60	10	290	Example
17	K	650	3.6	36	2.3	812	848	840	60	20	270	Example
18	L	600	3.2	50	1.6	825	875	830	75	25	240	Example
19	M	550	3.6	36	2.3	712	748	730	70	15	280	Example
20	M	700	3.6	36	2.3	862	898	880	70	15	280	Comparative example

* Underline designates outside the range of the invention.

Table 2-2

Steel sheet No.	Steel No.	Coiling temperature (°C)	Hot-rolled sheet thickness (mm)	Cold-rolling reduction (%)	Cold-rolled sheet thickness (mm)	[Coiling temperature + cold-rolling reduction percentage x 4.5] (°C)	[Coiling temperature + cold-rolling reduction percentage x 5.5] (°C)	Maximum heating temp. (°C)	Holding time in heating temp. region (s)	Average cooling rate (°C/s)	Temp. of forcefully stop cooling (°C)	Remark
21	N	550	3.6	56	1.6	802	858	840	60	20	250	Example
22	O	500	3.2	69	1.0	811	880	840	90	35	210	Example
23	P	600	3.2	44	1.8	798	842	820	90	15	240	Example
24	Q	600	3.6	36	2.3	762	798	780	80	15	270	Comparative example
25	R	550	3.2	38	2.0	721	759	740	60	20	260	Comparative example
26	S	550	3.2	44	1.8	748	792	760	60	15	250	Comparative example
27	T	600	3.2	50	1.6	825	875	830	75	25	240	Comparative example
28	U	500	3.2	50	1.6	725	775	750	70	15	260	Comparative example
29	G	600	2.0	50	1.0	825	875	840	90	40	340	Example
30	V	600	2.0	50	1.0	825	875	840	90	15	250	Example
31	W	480	2.3	57	1.0	737	794	780	90	10	300	Example
32	H	500	3.2	50	1.6	725	775	730	45	15	320	Example
33	X	580	2.6	62	1.0	859	921	885	300	15	250	Example
34	P	600	3.2	63	1.2	884	947	910	360	15	300	Example
35	P	600	3.2	44	1.8	798	842	910	300	15	300	Comparative example
36	Y	500	2.8	64	1.0	788	852	800	60	50	350	Comparative example
37	Y	610	2.8	61	1.1	885	946	902	60	20	280	Example
38	Z	520	3.2	50	1.6	745	795	770	130	30	260	Example
39	ZZ	620	2.4	33	1.6	769	802	790	90	15	250	Example

* Underline designates outside the range of the invention.

Table 3-1

Steel sheet No.	Steel No.	Tensile strength (MPa)	Elongation (%)	Area percentage of ferrite (%)	Area percentage of martensite (%)	Area percentage and kind of other phase (%) (kind)	Ratio of intervals of martensite	Nano hardness of martensite (GPa)	TS*El balance (MPa•%)	Absorbed energy* ($MJ•m^{-3}$)	Absorbed energy* per TS 1 MPa ($MJ•m^{-3}•MPa^{-1}$)	Remark
1	A	843	19.5	70	30	0	1.36	9.4	16439	88.8	0.105	Example
2	A	820	18.9	75	25	0	0.71	9.3	15498	77.9	0.095	Comparative example
3	B	886	18.1	60	40	0	1.50	8.0	16037	88.8	0.100	Example
4	B	852	17.8	70	30	0	1.59	7.2	15166	78.4	0.092	Comparative example
5	C	821	21.6	65	35	0	1.26	10.5	17734	94.4	0.115	Example
6	C	842	18.3	55	45	0	1.57	10.2	15409	79.1	0.094	Comparative example
7	D	708	24.0	80	20	0	1.13	9.3	16992	75.8	0.107	Example
8	E	621	27.1	80	20	0	1.21	9.5	16829	65.8	0.106	Example
9	E	673	23.2	70	30	0	1.57	7.4	15614	62.6	0.093	Comparative example
10	F	834	21.8	70	30	0	1.29	11.6	18181	100.1	0.120	Example
11	F	808	19.1	70	30	0	1.29	7.2	15433	75.1	0.093	Comparative example
12	G	867	20.6	60	40	0	1.15	12.7	17860	104.9	0.121	Example
13	G	821	18.8	60	40	0	1.15	7.5	15435	78.8	0.096	Comparative example
14	H	849	21.5	65	35	0	0.95	12.1	18254	100.2	0.118	Example
15	I	854	19.7	75	25	0	1.02	9.6	16824	90.5	0.106	Example
16	J	803	23.1	80	20	0	1.20	10.6	18549	95.6	0.119	Example
17	K	857	20.9	75	25	0	1.05	12.7	17911	99.4	0.116	Example
18	L	754	21.5	85	15	0	1.33	9.7	16211	80.7	0.107	Example
19	M	839	21.5	65	35	0	1.10	11.2	18039	96.5	0.115	Example
20	M	880	17.6	55	45	0	1.59	10.2	15488	83.6	0.095	Comparative example

* Underline designates outside the range of the invention.

Table 3-2

Steel sheet No.	Steel No.	Tensile strength (MPa)	Elongation (%)	Area percentage of ferrite (%)	Area percentage of martensite (%)	Area percentage and kind of other phase (%) (kind)	Ratio of intervals of martensite	Nano hardness of martensite (GPa)	TS*El balance (MPa•%)	Absorbed energy* ($MJ \cdot m^{-3}$)	Absorbed energy* per TS 1 MPa ($MJ \cdot m^{-3} \cdot MPa^{-1}$)	Remark
21	N	892	21.1	60	40	0	1.00	13.4	18821	107.9	0.121	Example
22	O	822	22.7	70	30	0	1.27	12.1	18659	97.0	0.118	Example
23	P	849	21.0	65	35	0	1.25	11.8	17829	97.6	0.115	Example
24	Q	531	29.2	95	5	0	1.72	7.6	15505	52.0	0.098	Comparative example
25	R	793	18.2	75	25	0	1.58	7.4	14433	75.3	0.095	Comparative example
26	S	559	27.1	85	15	0	1.73	7.2	15149	52.5	0.094	Comparative example
27	T	973	14.3	60	40	0	1.62	7.8	13914	89.5	0.092	Comparative example
28	U	1054	13.9	45	55	0	1.67	9.5	14651	97.0	0.092	Comparative example
29	G	825	20.1	60	40	0	1.15	8.9	16583	89.1	0.108	Example
30	V	639	26.3	70	25	5 (bainite)	1.14	8.5	16806	66.5	0.104	Example
31	W	789	21.2	73	18	9 (bainite)	1.18	9.3	16727	86.0	0.109	Example
32	H	783	21.5	63	30	7 (bainite)	0.95	12.1	16835	82.2	0.105	Example
33	X	877	21.5	56	44	0	1.00	12.2	18856	108.7	0.124	Example
34	P	881	21.4	62	38	0	1.02	13.3	18853	107.5	0.122	Example
35	P	910	18.1	43	55	2 (bainite)	1.05	7.3	16471	82.8	0.091	Comparative example
36	Y	622	26.2	90	10	0	1.45	7.1	16296	57.8	0.093	Comparative example
37	Y	701	27.2	74	24	2 (austenite)	1.05	10.3	19067	85.5	0.122	Example
38	Z	825	22.2	82	18	0	1.17	10.7	18315	92.4	0.112	Example
39	ZZ	873	21.3	72	28	0	1.22	10.8	18595	98.6	0.113	Example

* The value up to 10% strain at 10 s^{-1} of strain rate.

* Underline designates outside the range of the invention.